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ABSTRACT

The nature of qualitative understanding and associated learning processes in the context of a computer simulation called the "Envisioning Machine" (EM) are investigated. The questions focused on in this paper include the following: What sorts of knowledge do students' construct? What role does prior knowledge play in the construction of new knowledge? How does students' knowledge compare to scientists' knowledge? The researcher argues that students construct three kinds of knowledge through their experiences with the EM: registrations, qualitative cases, and p-prims (generative metaphors). Students' registrations are ways of carving up the simulation into parts, labelling part, and selecting some labelled part for attention. Students' qualitative cases are schema composed of qualitative associations that share applicability conditions. Students construct integrative explanations by applying p-prims to the features they register. An example of student dialogue that strongly suggests progress towards an understanding that occurred during a session with EM is included and is referred to throughout the paper. Some recommendations for curriculum and teaching and a list of 40 references are included. (KR)

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MicroAnalysis of Qualitative Physics: Opening the Black Box

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MicroAnalysis of Qualitative Physics Learning: Opening the Black Box

For several years I have been investigating the nature of qualitative understanding and associated learning processes in the context of a computer simulation called the "Envisioning Machine" (EM). My investigations started with the hope the technology could succeed where conventional curricula had failed; although technology would be no panacea, computers might be a revolutionary tool. Extensive time spent with students who volunteered to test the EM, and even more time spent watching video recordings of students' learning has tempered my optimism for technological fiat. But more significantly, careful analysis of students' learning processes has opened a broader and richer set of questions about the nature of students' knowledge, scientific knowledge, social interaction, and interactive technology.

In this paper, I focus on a particular set of questions the knowledge resulting from students' experience with the EM: What sorts of knowledge do students' construct? What role does prior knowledge play in the construction of new knowledge? How does students' knowledge compare to scientists' knowledge?

My concern in addressing these issues is with the picture of students and scientists that emerges from current research on science education. The picture is one of a broad gulf, lined with obstructions and pitfalls. Indeed, the vastness of this gulf, as portrayed in science education research, makes learning seem nearly impossible. Misconceptions research (e.g. McDermott, 1984; Eylon and Linn, 1988; Confrey, 1990) has seized upon a growing list of inadequacies in the nature of the science student, and declared those to be the root of the problem: students' perception misleads them (Trowbridge and McDermott, 1980), they focus attention on the wrong features (Anzai and Yokohama, 1984), they lack procedural skills (Heller and Reif, 1984), they have inappropriate prior beliefs (e.g. McCloskey, 1983), are unable to separate theory from evidence (Kuhn, Amsel, and O'Loughlin, 1988), and have metacognitive weakness (Songer, 1989; Hammer, in preparation). Expert-novice research, on the other hand, is producing an equally long list of the ways in which science experts are qualitatively different from science students (e.g. Larkin, 1983; Chi, Feltovich, and Glaser, 1980). The net result is an increasingly divergent account of students and scientists, and growing talk of learning in terms of radical change — conflicting, confronting,

overcoming, replacing, eliminating, etc. (e.g. Champagne, Gunstone, and Klopfer, 1985) — rather than organic growth. These metaphors portray learning as discontinuous, and therefore not achievable through incremental transformation and reconceptualization.

In contrast, I contend that radical change is needed not in students' heads, but in science education researchers' conceptions of students' and scientists' knowledge. The dichotomies that separate learner from curriculum are *constructed*, not inherent. In particular, the dichotomies are presumed by the definitions of curriculum in terms of "concepts" and student knowledge in terms of "misconceptions." The definition of students' knowledge as "misconceptions" construes prior knowledge as static, tainted, and inferior. This particular construal, I contend, is both false and misleading. Students' knowledge is fluid and germinal — it is the prime resource that students have with which to construct qualitative understandings. Dichotomies between student and curriculum are a consequence of holding either the conception of students' knowledge or the conception of the curriculum as fixed and inviolate. A critical issue facing science education is replacing these dichotomies with dimensions of continuity that enable organic growth of scientific knowledge from its roots in commonsense experience.

Microanalysis is a useful tool for the necessary reconstruction of our conception of students' knowledge and the science curriculum. As discussed in the companion papers in this symposium (Smith, 1991; Kindfield, 1991; Magidson, 1991; Meira, 1991; Moschkovich, 1991), microanalytic research emphasizes detailed examination of rich behavioral records of individual instances of learning and reasoning process. The process emphasizes accountability of the analysis to the complete record of the events that transpired. This push for accountability provides just the kind of effort that is need for new ways of seeing the student and the curriculum to emerge. By documenting students' developing understanding in terms more appropriate to the nature of students' experience, one can begin to see the possibility of achieving scientific understanding through incremental reformulation of commonsense knowledge.

In this short paper, I report on my research about students' learning with the Envisioning Machine, summarizing the issues discussed in depth in Roschelle (1991). I start with a brief example of a important learning event and show how our existing categories give a weak accounting of the event. I then summarize a perspective that provides a more adequate account. Finally, I conclude with some recommendations for the curriculum and teaching.

Learning With the Envisioning Machine: An Example

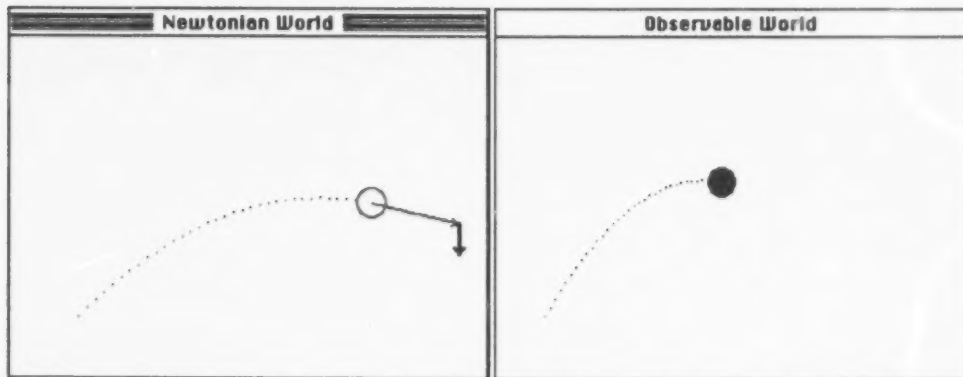
The Envisioning Machine

I briefly describe the EM here, so as to set the context. Interested readers can find more detailed descriptions in Roschelle (1990) and Roschelle (1991). The Envisioning Machine (EM) is a direct-manipulation, graphical simulation of the concepts of velocity and acceleration (Figure 1). It elaborates upon earlier Newtonian Microworlds (e.g. diSessa, 1982; White, 1984; White & Horwitz, 1987) by explicitly representing velocity and acceleration as two dimensional vectors.

The screen of the EM is divided into two windows, the "Observable World" and the "Newtonian World." The Observable World displays a ball and the Newtonian World displays a particle with attached velocity and acceleration vectors. The students' goal is to manipulate velocity and acceleration vectors in the Newtonian World in order to match motions of the ball in the Observable World. In order to do this, students must learn about the meanings of the vectors. They learn by experimenting with the behavior of the simulation.

When I designed and built the EM, my assumption was that it would help students to learn physics (Roschelle, 1986). Since any such claim begs for empirical evidence, I began to assess what students learned from the EM. This would seem to be an easy thing to do: let students use the program and then test them for understanding of velocity and acceleration. Following the conventional assessment strategy, I looked for (1) ability to express the concepts of velocity and acceleration and (2) ability to apply the concepts to standard problems.

Figure 1: The Envisioning Machine



Although it is unlikely that students would express the concepts exactly as they appear in textbook, it is plausible that students would express a conception of velocity and acceleration in their own words, and that this conception might be compatible with a scientific conception of velocity and acceleration. This plausibility was based on the assumption that the visual, dynamic model presented in the EM was like a scientist's "mental model" and could provide the basis for students to construct their own internalized knowledge about velocity and acceleration (Roschelle, 1986; Greeno, 1989). If students were able to construct appropriate knowledge from their interaction with the Envisioning Machine's external models, they could plausibly gain ability to give qualitative predictions and explanations that are compatible with scientific theory.

The Primary Episode

The transcript below presents an example of a student dialog that strongly suggests progress towards an understanding. This dialog occurred between two high school girls about 20 minutes into their first session with the EM. I call them "Carol" and "Dana." The nouns in square brackets were determined primarily from the students' gestures and secondarily from the overall context. For sake of reference, throughout the paper, I will refer to this episode of Carol and Dana's behavior as the "primary episode." The paper will consider additional data, but continually return to this primary episode.

- C: Look that arrow [vel arrow] is growing that
 D: I know
 C: arrow grows!
 C: hhh. hhh. hhh. ((laughing))
 D: I know I saw it last time, it's like, oh no!
 C: So that means as it [the particle] picks up speed it [vel arrow] grows, so this [acc arrow] probably determines how much it [vel arrow] grows by.
 D: oh:::
 C: and that [vel arrow] is the starting speed. The first one's [vel arrow] probably the starting speed and this [acc arrow] is how much it like pulls it [vel arrow], like how much it [vel arrow] grows by
 D: so:::
 C: so if it's [acc arrow] a lot it's [vel arrow is] probably going to grow by more, so the starting speed is really slow

The content of Carol's last three turns in the primary episode seemingly articulates a concept of the EM vectors that is reminiscent of the definitions of velocity and acceleration. In these definitions, velocity corresponds to the instantaneous speed and direction of motion and acceleration corresponds to the rate of change of velocity.

To be sure, it is unlikely that Carol and Dana's knowledge at the time of this dialog was exactly equivalent to a scientist's knowledge of velocity and acceleration. For example, the conventional scientific representations of velocity and acceleration use definitions expressed in terms of derivatives with respect to time: Acceleration is the derivative of velocity with respect to time, and velocity is the derivative of position with respect to time. Carol and Dana had not yet taken calculus, so it is implausible that their knowledge was formulated in exactly these terms.

As a consequence, the strongest plausible claim is that the student's knowledge is compatible up to the level of qualitative reasoning. Carol and Dana's statements can be mapped onto qualitative scientific statements about velocity and acceleration. In particular, Carol and Dana described acceleration as a rate of change of the velocity vector ("so this [acc arrow] probably determines how much it [vel arrow] grows by"). They also connected the velocity arrow to initial speed ("starting speed") and connected the change in the velocity arrow to the change in the speed of the motion ("as it [the particle] picks up speed it [the vel arrow] grows"). The students also made a correct inference about the effect of increasing acceleration ("if it's [acc arrow is] a lot it's [vel arrow is] probably going to grow by more"). Especially when compared with the knowledge that the students articulated earlier (documented in Roschelle, 1991), this episode did mark progress towards a functional understanding of the EM that is more compatible with scientific theory.

The Romantic and The Skeptic

There are two obvious responses to a presentation of this sort of data, which can be labelled the "Romantic" and the "Skeptic." The Romantic leaps to a conclusion, "Carol and Dana have constructed their own understanding of velocity and acceleration. In fact, because they built the concept themselves from experience and expressed it in their own words, it will be especially meaningful and robust." The Skeptic, on the other hand, denies the portent of this episode, "Sounds to me like they're talking about pictures of arrows growing and pulling. How do I know

that they've learned anything about the real-world or about scientific concepts? Seems like another video game to me."

In fact, a careful microanalysis shows that neither the Romantic nor the Skeptic is correct. On one hand, the Carol and Dana's conversation shows considerable progress in connecting their commonsense concepts to scientific concepts (pulling/growing connected to change of velocity over time) and in mapping surface features to deep features (the perceived "starting speed" to velocity and the perceived speed-up to the change in velocity). On the other hand, there was ample evidence that the students' understanding of the velocity and acceleration was not complete. Thus the Romantic does the students a dis-service by ignoring the ways in which their knowledge still needs considerable development to become scientific. The Skeptic, however, neglects an important step towards an understanding, and thus misses an opportunity to help the students develop knowledge that is more like scientific knowledge.

Instead of taking positions with either the Romantic or the Skeptic, I argue that analyzing understandings requires a richer, more complex view of students' knowledge. Education does not require black and white categorizations of understanding versus mis-understanding — rather it needs articulation of gray areas and directions for change. The challenge for science education therefore is to construct a more truthful account of student's evolving knowledge: one that will give students credit for what they learn and know, while differentiating partial states of understanding from more complete states of understanding. As I have foreshadowed above, and expound further below, the core idea I invoke is the notion of a distributed encoding, whereby understanding of specific scientific laws and definitions is composed of many interacting elements in an extended system of knowledge. I analyze learning as the transformation of students' existing knowledge through a process of incremental reformulation.

Qualitative Understanding

A significant issue that must be discussed in order to transcend the gulf between the Skeptic and the Romantic is the nature of qualitative understanding. In order to claim progress for Carol and Dana, it is necessary to say something about what an acceptable qualitative understanding would look like. In Roschelle (1991), I argue that the knowledge that students construct through

their experience with the Envisioning Machine has three components: registrations, qualitative cases, and p-prim applications. Brief descriptions of these kinds of knowledge are as follows:

- registrations:* features that are perceived, labelled, and selected for attention
- qualitative cases:* schemata for qualitative problem solving
- p-prims:* generative metaphors used to construct explanations

The notion of qualitative cases has been most strongly developed in Artificial Intelligence research on qualitative reasoning (e.g. Bobrow, 1986; Forbus and Gentner, 1986). A theory of p-prims as elements of knowledge is the centerpiece of diSessa's developmental epistemology of physics (1983;1987;1988).

My claim is that analysis in terms of these components allows the Romantic-Skeptic dichotomy to be replaced with a more useful description of students' knowledge state: unlike the Skeptic's view, students are given credit for constructing valuable partial understandings even if they fall short of scientific understanding, and unlike the Romantic's view, students' own constructions are not construed to be more like scientific understandings than they actually are. Furthermore, by analyzing knowledge in terms of these three components, it is possible to describe diverse states of partial understanding, and also to describe trajectories of development that lead to fuller understandings. The sections below illustrate the application of these categories of analysis to Carol and Dana's work.

Registrations

By registrations, I refer to the way students carve up their sensory experience, give labels to parts, and assign those labelled parts significance. In particular, I refer to the way the students carve up the array of pixels on the Envisioning Machine into objects, properties and relations, give labels to those parts, and decide which ones are important. The key finding is that students do not automatically have the same registrations as scientists or educators (see also Meira, 1991). The discussion below examines two related registrations, "starting speed" and "growing" that contributed to learning impasses and breakthroughs.

In the ten minutes preceding the primary episode, Carol and Dana experienced difficulties with registering speed as a scientist would. This led to a series of problem solving impasses. One particularly deep impasse was reached when Carol and Dana rejected meanings for velocity and

acceleration that were close to the scientific definitions in favor of alternative meanings that contradicted the scientific definitions. This occurred as follows:

At the beginning of their problem solving attempt, Carol and Dana constructed associations for velocity and acceleration that appeared to be correct propositional statements of the qualitative definitions of velocity and acceleration. For instance, Dana said "Maybe this arrow [acc] controls the speed it picks up with," an apparent reference to acceleration as a rate of change of speed. The students then set up an experiment in which they tried "extremes" of velocity and acceleration to test their ideas. They made velocity very small and acceleration very large. However, when they watched the computer simulation run, Dana said "When we made this arrow [vel arrow] shorter it picked up speed slower." Thereby she registered the outcome of the experiment as a slower rate of increase in speed, rather than a slower initial speed.

Dana and Carol then reversed the roles of velocity and acceleration, saying:

- D: So maybe now this arrow [vel] is how fast it picks up speed.
C: And this one [acc arrow] is how fast it is?
D: Right.

Additional data analysis (in Roschelle, 1991) suggests that this mistaken reversal of the meanings of velocity and acceleration vectors was due to registration problems surrounding their description of speed. In particular, the students registered the feature they called "speed" by looking at the amount of comparative distances the objects covered in the Newtonian World and the Observable World. If one registers speed this way, it is difficult to distinguish a high initial speed from a high acceleration — all one can really see is the average speed: When the students talked about speed, they did not at first distinguish initial speed, final speed, and average speed, as evident in the phrase "how fast it is." Moreover, even though scientists clearly see the speed increasing continuously in the EM, the students were not sure whether the speed was increasing continuously, or in one discrete jump. Indeed, just before their primary episode, Carol and Dana discussed their interpretation of the spacing of the dots:

- D: So how are we supposed to know if the dots being closer together means its just going slower, so we change this arrow [vel]
C: I think it just does.
D: Or it means its picking up speed slower, this arrow [acc]
C: I think its a combination of both

Notice that neither Carol and Dana were sure how to register the dots: Is the close spacing relevant to velocity, acceleration, or both?

Given this history, the events of the primary episode take on more significance. In particular, in the primary episode, Carol and Dana described initial speed for the first time: Carol said, "that [vel arrow] is the starting speed." This was the first time that they used the phrase "starting speed" in distinction to just "speed." Connecting velocity to starting speed is an important step towards understanding velocity and acceleration. Indeed, in conjunction with this new description, Carol and Dana switched back to the correct associations for velocity and acceleration that they had formed earlier.

Despite the fact that the Carol used the description "starting speed," it is not clear that the students could register "starting speed" as a distinct feature of the simulation display. Soon after the primary episode, this issue was firmly resolved:

- D: How can you tell if its the speed its going at?
The first arrow, the normal arrow [velocity]
- C: Wait, the starting speed?
- D: The starting speed
- C: cause look at the starting speed (points to beginning), cause see the starting speed is about exactly the same (gestures back and forth) so it must be the (inaudible) because see the starting speed is the same but then it gets farther, so I think its that the second arrow [acc]. So I think the second arrow [acc] pulls it out. I think the first arrow [vel] is the starting speed and depending on like the second arrow is how fast it pulls it.

In her last phrase, Carol connected the starting speed to the spacing of the first few dots via a gesture; she gestured to the first few dots of each motion. This was the first time that the students carved up the sequence of dots to form a registration of initial speed as distinct from average or final speed. As it turns out, many students do not interpret the spacing of the trace dots as indicators of instantaneous speed as a scientist would. More typically, students see the dots merely as indicators of path. Thus, one advance of the primary episode was the differentiation of initial speed from other descriptions of speed, and specification of a means for more directly registering the comparative value of initial speed.

A related advance was Carol and Dana's sudden attention to the growth of the velocity vector. In the ten minutes prior, Carol and Dana never mentioned the visible change in the velocity vector. Their breakthrough followed upon their increased emphasis on this feature:

- C: Look that arrow [vel arrow] is growing, that
D: I know
C: arrow grows!

By making this sensory experience into a named process, a "growing," Carol and Dana made it available for the first time as part of an explanation.

Interestingly, one of the first things most scientists or educators comment on when using the EM is that the velocity arrow changes as the simulation runs - by watching the change of velocity over time, one can directly see the effect of acceleration. This is an obvious "part" of the display for scientists, it has a conventional label ("velocity change") and is clearly noteworthy. In contrast, students sometimes use the EM for hours without noticing this part of the display at all. Or as one student said, "I noticed it but I didn't think it was important."

By considering these two registrations — growing and starting speed — one can account for the breakthrough Carol and Dana experienced in the primary episode. Although they had formed qualitative associations compatible with scientific theory prior to this episode, they registered *average* speed, but the *initial* length of the velocity arrow. The incommensurability of these registrations led them to reject their correct associations and form unscientific ones instead. In the primary episode, Carol and Dana overcame this impasse by linking initial speed (the first few dots) to the initial length of the velocity vector, and linking the increase in speed to the growth of the velocity vector over time. Thus they sorted out their perceptions into associations between (a) *initial* speed and *initial* length, and (b) *increase* in speed and *increase* in length.

The registrations of growth and speed were particularly significant to Carol and Dana's primary episode. But they are not the only registrations that were problematic for Carol and Dana or for other students (Roschelle, 1991). Students' registrations diverge from scientists in numerous, unpredictable ways. For example, students registered speed only in terms of positive values, whereas scientists use both positive and negative values. Specifically, students described a vertical toss of a ball as decreasing and then increasing speed, whereas scientists describe a continual downwards acceleration. As a consequence, students face impasses in explaining what

appears to them to be a sudden switch from *decreasing* to *increasing* speed. (Goldberg and Anderson, 1989, as well as diSessa, Hammer, Sherin, and Kolpakowski, in press, discuss similar findings about students.) Such registrations can throw students' learning off track, at least temporarily. Carol and Dana, for instance, had trouble generalizing their explanation to the vertical toss motion. To a scientist, both the straight-line speed up and vertical toss motions have the same explanation; both are linear motions with constant acceleration. To a student, on account of their registrations, these motions may appear to have little in common.

The phenomena of divergent registrations puts a damper on one of the great hopes of Romantic technologists — just give the students the "right experience" and learning will be error-free and painless. In fact, students do not automatically register experiences the same way scientists or curriculum designers do. As a consequence, one can never predict exactly how students will carve a sensory experience into parts, what labels they will give to parts, and what significance they will assign to various labelled parts. Therefore, what is obviously the "right experience" from an designer's point of view may turn out to be a completely different experience for the students.

Qualitative Cases

A qualitative case is a schema for qualitative problem solving, consisting of a set of qualitative associations that share the same applicability conditions. During their experience with the EM, students develop cases that are identified with qualitatively different trajectory shapes (Roschelle, 1991). Typically these cases include a parabolic case, a straight-line speeding up (SLSU) case, a vertical toss case, and a zero speed-zero acceleration (stopped) case. The key finding is that students rapidly construct heuristic associations adequate for problem solving in each case, but those associations may not include enough knowledge to support an integrated understanding across cases.

Carol and Dana's primary episode illustrates the construction of qualitative case knowledge. Two important forms of qualitative case knowledge are configuration conditions and qualitative proportionalities. Each is discussed briefly below:

A configuration condition links the shape of the trajectory to the shape of the initial conditions. In particular, early in the challenge they were working on, Carol and Dana discovered

that pointing both acceleration and velocity in the same direction resulted in the qualitative class of motion they were interested in matching, an SLSU motion. Such configuration conditions are useful elements of knowledge. For example, when the students later encountered another linear motion that sped up, they could immediately put the vectors in the correct direction. Likewise, if asked "What would happen if both initial velocity and acceleration were put in the same direction?" Carol and Dana could readily answer, "It would go in a straight line and speed up."

Although configuration conditions (CCs) are useful components of knowledge, they are quite limited. For example, this particular CC does not include information about the lengths of the vectors. Thus when trying to match a particular SLSU motion, Carol and Dana were not sure about the relative effects of changing the velocity arrow versus changing acceleration arrow. Furthermore, the CCs are not self-explanatory: it is not clear *why* aligned vectors should result in a motion that speeds up, rather than slows down, or just goes at a faster constant speed.

A complementary form of knowledge is the Qualitative Proportionality (QP). A QP relates two variables by an unspecified monotonic function. In this case, relevant QPs are "length of velocity arrow QP initial speed" and "length of acceleration QP rate of speed increase." Part of Carol's insight involved articulating these two QPs: "this [acc arrow] probably determines how much it [vel arrow] grows by and that [vel arrow] is the starting speed."

These knowledge elements are also quite useful. For example, knowledge of the first QP enables students to adjust the length of the velocity vector to match the desired initial speed. QPs also are limited. For instance, Carol said, "so if it's [acc arrow] a lot it's [vel arrow is] probably going to grow by more." In this statement it is not clear *how much more* the velocity will grow by. That is QPs do not imply particular quantitative relationships, for example linear or quadratic functions. In fact, qualitative reasoning cannot distinguish a constantly increasing linear function from a constantly increasing quadratic function.

To summarize, in this episode, Carol and Dana constructed knowledge for a particular case, straight-line speeding-up (SLSU) motion, consisting of one configuration condition (both arrows aligned) and two qualitative proportionalities (vel QP instantaneous speed, acc QP rate of speed increase). These knowledge elements do not necessarily imply a correct model of velocity or acceleration at either the causal or quantitative level, but they do imply some useful problem

solving knowledge. In particular, Carol and Dana were able to solve the next SLSU motion problem quite rapidly by re-applying the CC and QPs they constructed for this motion problem.

Recognizing the case structure of students' knowledge has important implications for analyzing the power and limits of students' knowledge. Recall that the Romantic leaps to the conclusion that Carol and Dana have constructed the scientific concepts of velocity and acceleration. In contrast, I have suggested that they construct QPs and CCs for a particular case. When one adopts this perspective, it becomes clear that students need not construct the scientific definitions of velocity and acceleration in order to solve EM problems.

Roschelle (1991) documented the CCs and QPs used by students in each qualitative case. The associations for vertical toss and parabolic cases are particularly striking. Students often solved the vertical toss with associations relating to the height of the apex and the total trip time:

Longer velocity increases the height and the total trip time.

Longer acceleration decreases the height and the total trip time.

Students would then engage in "balancing out" the two lengths so as to achieve the desired height and total trip time simultaneously. Similarly, students often solved parabolic motions using associations that relate the *width* of the parabola to the *angle* between the velocity and acceleration vectors: the closer velocity and acceleration are to being co-linear, the narrower the resulting trajectory.

Although these associations have heuristic value, they do not directly encode the scientific view of the matter. Note that the associations are not in error: they are valid case-specific regularities, and thus not misconceptions. Rather they differ from the scientific view in priority. A scientist would not dispute that height increases with velocity in the vertical toss, but would hold this to be a derived regularity, not a first principle. The scientists' derivation would start from initial speed and change in speed, and derive associations regarding the height of the apex.

Students do not necessarily build qualitative cases that emphasize the same knowledge elements that a scientist would. As a consequence, cases tend to accumulate disjunct and fragmentary chunks of heuristic know-how which do not necessarily support knowing why. Moreover, generalization across cases becomes problematic. For example, it is difficult to generalize across the qualitative cases for SLSU and vertical toss motion, because each emphasizes different constituent associations. Indeed, the case that Carol and Dana constructed

in the primary episode emphasized initial speed and speed increase, whereas the case they constructed for the vertical toss case emphasized the height of the apex and total trip time. Despite many insights, they were not able to build an integrated understanding of these two motions during the two sessions in which they used the EM. This observations may shocking to the physicist, for both motions are instances of linear, constantly accelerating motions, and thus transfer should be immediate and obvious.

The moral is that student construct knowledge is less general and more case specific than often appears. Indeed, in the context of the EM, the Romantic who jumped to the conclusion that students had constructed "understanding of velocity and acceleration" would be more often wrong than right. The safe assumption is that students constructed a qualitative case with correct configuration conditions and qualitative proportionalities. On the other hand, the Skeptic would be wrong to dismiss these elements of knowledge as "misconceptions" because of their limits. Within the appropriate scope, qualitative cases encode useful know-how for making scientific predictions and giving scientific explanations.

P-prims

Qualitative cases develop from a bottom-up form of knowledge construction: students register particular features of the simulation and hypothesize various CCs and QPs to link them. For example, students see the length of the velocity arrow as an important parameter, and experiment with linking it to speed or height of trajectories. By hypothesizing and experimentally confirming various combinations of pairs of parameters in specific circumstances, students build up qualitative case knowledge.

An analysis solely in terms of registrations and qualitative cases suggests that students will tend to construct fragmentary collections of heuristic associations, which may or may not be consistent with a scientific understanding of velocity and acceleration. An additional form of knowledge construction can counteract this tendency: the application of generative metaphors (p-prims) to structure clusters of experienced regularities.

In Carol and Dana's insight, the pulling p-prim was applied to acceleration and velocity: "The first one's [vel arrow] probab!y the starting speed and this [acc arrow] is how much it like pulls it [vel arrow], like how much it [vel arrow] grows by." Pulling is a powerful metaphor

because it organizes several salient regularities of the EM: (1) that acceleration is attached to the tip of velocity, (2) that acceleration points in the direction of velocity changes, and (3) that a longer acceleration results in more velocity change.

By applying pulling in this way, students can form a bridge across the gulf between their understanding and scientific understanding. This use of pulling connects to their understanding, because in everyday experience a pull is a directed force applied by contact with an object, that makes it move in the given direction, with proportional speed. Thus by applying pulling to acceleration students can associate velocity change with a familiar process. At the same time, this use of pulling maps to the scientific understanding of acceleration at the level of qualitative reasoning: acceleration is a directed change in velocity over time.

P-prims function as pre-made explanatory structures that can be adapted to make sense of complex new phenomena at a level more integrated than an arbitrary set of CCs and QPs. Pulling was not the only p-prim that students employed — guiding, balancing, resistance, attraction and stretching were also common. Not all of these p-prims lead to explanations of the EM that are consistent with scientific explanations. Indeed, the pulling p-prim itself can be applied in diverse ways, some compatible with scientific explanations and others which are not.

In Roschelle (1991), 14 students who used the EM for two sessions were divided into two groups. The division was based on students' trends of p-prim use. Students whose trends showed increasingly consistent use of pulling to explain the EM across cases were placed in one group. These students gave explanations similar to Carol and Dana's pulling-based explanation, but for all cases of motion. The other group either (a) used different abstractions to generate explanations or (b) never stabilized on a single abstraction. The pulling group scored significantly better on a post test measuring qualitative understanding. This provides evidence for the claim that use of the pulling p-prim accounts for students construction of an integrated explanation of velocity and acceleration.

This phenomenon deserves some discussion. Researchers have tended to sort students' abstractions into two categories: misconceptions and concepts. Pulling, however, appears to be neither. Pulling is similar to the familiar misconception of "force as a mover" which holds that the direction and length of a force is directly related to the direction and speed of motion. When applied to a force such as gravity and the motion of a particle, force as a mover is unlike a

scientific explanation. However, when applied to acceleration and the change in velocity, force as a mover is a perfectly good explanation: in velocity space, the tip of velocity does move in the direction indicated by acceleration with speed proportional to the length of acceleration. Thus whether pulling is a misconception or not depends critically on its application.

In fact, when Carol and Dana encountered the reverse case, they re-applied the pulling metaphor to make sense of ball toss. However, in doing so, they reasoned that velocity pulls the ball up, and the acceleration pulls the ball down. This use of pulling is unscientific because the students directly related acceleration to the downwards motion, as in the common misconception. Thus Carol and Dana simultaneously exhibited a use of pulling that was a "scientific concept" and a use of pulling that was a "misconception."

The moral is that there is no sense in treating students' stock of abstractions as "concepts" or "misconceptions." Force as a mover can be both. (Indeed, physics textbooks frequently draw on this fact in sections on electricity, when they tell students that the drift velocity of electrons is proportional to electro-magnetic force, an authorized use of the "misconception" that velocity is proportional to applied force.) Instead, students' abstractions should be viewed as generative metaphors. These metaphors are essential to forming an integrated explanation that generalizes across qualitative cases (see also Clement, Brown, and Zietsman, 1989). Such learning is critically dependent on the use of the metaphor: some uses diverge from scientific understanding, while others converge towards scientific understanding.

Summary

The three preceding sections discussed three components of knowledge independently — registrations, qualitative cases, and p-prim uses. With the components of registrations, qualitative cases, and p-prims in mind, the import of Carol and Dana's primary episode can be summarized as follows:

Registrations

Around the time of this episode, Carol and Dana began to carve up the motion into "starting speed" and pay attention to the "growing" velocity arrow. They registered starting speed by looking at the spacing of the first few trace dots. They registered the rate of speed

change by first matching the starting speed, and then comparing the distance travelled. These registrations represent a change from their earlier registrations, which attended to distance both as speed and rate of speed change. As a consequence of their earlier registrations, Carol and Dana found evidence against valid regularities and in support of mistaken regularities. As consequence of now registering initial speed, change in speed and distance as distinct, Carol and Dana were now able to verify and apply correct associations for velocity and acceleration.

Qualitative Cases

Carol and Dana constructed a qualitative case for straight-line speeding up (SLSU) trajectories. One main element of knowledge was the configuration condition (CC) that the directions of velocity and acceleration are aligned. The other main elements were the qualitative proportionalities (QPs) discussed in the insight. One QP linked initial speed to the initial length of velocity ("The first one's [vel arrow] probably the starting speed"). The other QP linked acceleration to the rate of increase of the length of velocity ("how much it grows by"). The students were later able to use the qualitative case to solve additional challenges, but were not able to generalize it to other cases.

P-prims:

In the primary episode, Carol applied the pulling p-prim in the form "acceleration pulls the tip of velocity" for the first time. This use of pulling is important because it provides grounds for mapping the students' knowledge to scientists' knowledge. Scientists think about the relationship between velocity and acceleration with one unifying concept, the derivative. Before the use of pulling p-prim, Carol and Dana were reasoning about the direction and lengths of velocity and acceleration with three individual knowledge elements (2 QPs and 1 CC). Their use of pulling provided an explanation of these knowledge elements in terms of a single unifying abstraction.

Knowledge System Properties

The conjunction of registrations, qualitative cases, and p-prims that Carol and Dana brought to bear in the primary episode formed a coherent whole: the registrations provided access to the necessary features of the display, the qualitative case knowledge provided associations between features that were useful for the students' problem solving, and the p-prims provided an

integrated explanation of the SLSU case. Furthermore, with regards to the SLSU case, the students' knowledge in the primary episode does map onto a scientific conception of velocity and acceleration. However, the students knowledge is only consistent with scientists' knowledge within the SLSU case — for other cases, the students developed other knowledge elements that do not map onto a scientists' qualitative knowledge. Moreover, the students knowledge was somewhat unstable: later experiences with other cases of motions led them to change their knowledge.

Rejoinders to the Romantic and the Skeptic

Recall that the Romantic jumped to the conclusion that Carol and Dana had arrived a scientific understanding in the primary episode. Through the detailed microanalysis, I argued that this conclusion is not supported by the data. Carol and Dana have constructed knowledge that is closer to scientific knowledge than the knowledge they started with. However, their understanding was homomorphic only with respect to a single case, SLSU motion. Moreover, their understanding was not stable, as slightly different motions (from a scientific point of view) led to rather dramatic revisions of their understanding, and in particular, caused their understanding to change for the worse.

The Skeptic, on the other hand, denied that the primary episode showed any progress at all. By analyzing the students' progress in terms of registrations, qualitative cases, and p-prims, the Skeptic, too was shown to be wrong. In the time leading up to the primary episode, Carol and Dana constructed new registrations, a new qualitative case, and a new use of a p-prim. Their integration of these components shows definitive progress towards a scientific understanding, although this progress was limited in scope.

Conclusions

What sorts of knowledge do students' construct?

I have argued that students construct three kinds of knowledge through their experience with the Envisioning Machine: registrations, qualitative cases, and p-prims. Their registrations are ways of carving up the simulation into parts, labelling parts, and selecting some labelled parts for attention. As students work with the EM, they change their registrations in multiple ways:

different clusters of pixels become available as parts (e.g. the first few trace dots), the students attach labels to those parts (e.g. "starting speed"), and focus attention more appropriately (e.g. on starting speed rather than distance covered).

Students' qualitative cases are schema composed of qualitative associations that share applicability conditions. Students construct associations in the form of qualitative proportionalities (e.g. "length of acc QP rate of speed increase") in order to solve EM problems more efficiently. Their construction of cases occurs through a hypothesis and test cycle: students propose particular QPs relating the features they register, and test the efficacy of those QPs in problem solving.

Students construct integrative explanations by applying p-prims — generative metaphors — to the features they register. In the primary episode, Carol and Dana used the pulling p-prim to integrate features they registered (e.g. "growing") and the associations in their qualitative case.

What role does prior knowledge play in the students' construction of new knowledge?

Misconceptions research has stressed the negative roles students' prior knowledge plays in school learning. In contrast, careful microanalysis highlights the mixed consequences of prior knowledge in students learning. Students constitute their developing theories by adapting prior knowledge to new experience. Some of their prior knowledge has a very general, structural form. For example, qualitative proportionalities provide a kind of relationship that students can instantiate with information relevant to particular problem solving situations. When different proportionalities are useful in different situations, students form qualitative cases. Other prior knowledge, like p-prims, are re-used by metaphorically applying their content to the new situations. For example, when Carol and Dana use the pulling p-prim, they cannot literally mean that some black pixels exert contact forces on other black pixels. Instead, they used pulling as a theory-constitutive metaphor that organizes their experience.

Use of prior knowledge in the form of registrations, structures for qualitative cases, and generative metaphors is the means that students have available to them to construct knowledge. By seeing only a negative role for this knowledge, we deprive students of the only means they have available for success.

On the other hand, it is important to recognize that scientific knowledge is hard to construct. Students' registrations often focus on the features of a situation that are not the ones most important to scientists. They construct qualitative cases that are considerably less general than the principles of science. P-prims like pulling can be used to construct theories that diverge from scientific principles just as easily as they can be used to construct theories that agree with scientific principles. Thus, while students knowledge is fluid and germinal, the construction of theories that agree with scientific notions is not pre-destined. Deep similarity to scientific ideas, as well as integration and stability within the students' set of ideas are difficult to achieve. Rather than focussing on isolated elements as "misconceptions" or "conceptions," and trying to confront, eliminate, replace, or overcome prior knowledge, educators should focus on shaping the resources students *do have* into knowledge systems that are homomorphic to scientists knowledge, stable and well-integrated.

How does students' knowledge compare to scientists' knowledge?

The most difficult issue facing science education discovering the dimensions of continuity that enable organic growth from the knowledge students already have to the knowledge science educators want them to have. I have argued that organic growth in students' knowledge occurs by transforming and restructuring students' registrations, qualitative cases, and their use of p-prims. What does this growth have to do with scientific knowledge?

If we look to the standard textbooks for our conception of what scientific knowledge is, the answer is not promising: the kind of knowledge that students construct has almost nothing to do with textbook science. Textbooks focus on knowledge in the form of equations. Four equations are commonly given in the chapter on velocity and acceleration: $v = x/t$, $a = v/t$, $x' = x + vt + 1/2at^2$, and $v'^2 = v^2 + 2ax$. The examination questions used to measure students' understanding require identifying which variables are given, selecting equations that have those variables, and solving the equations (as modelled in the work of Larkin, McDermott, Simon and Simon, 1980). These equations, and this problem solving process are not obviously similar to the registrations, qualitative cases, and p-prims that students construct using the EM. Therefore it is not necessarily true that using the EM will help students solve textbook problems, nor will

learning to solve textbook problems necessarily help students predict and explain the behavior of the EM.

By focussing on this discontinuity, however, educators miss an opportunity to restructure science education for the better. Although the knowledge students construct has little to do with textbook problem solving, it has a great deal in common with how scientists make qualitative predictions and generate qualitative explanations. If one looks at the history of science, problems with registrations, qualitative cases, and p-prims are apparent. For example, scientists had difficulties distinguishing heat from temperature — a registration problem (Wiser and Carey, 1983). Likewise, metaphors drawn from everyday experience were formative in the theories of Einstein, Maxwell, and other key figures (Boyd, 1986; Einstein, 1950; Lightman, 1989; Miller, 1986; Nercessian, 1988). Similarly, research in Artificial Intelligence (e.g. Forbus, 1984) has shown the importance of qualitative case knowledge to the kinds of qualitative reasoning scientists and engineers routinely engage in.

The problem is assumption that textbooks have “concepts” while students have “misconceptions.” Textbooks present only a narrow subset of the scientific meanings available to practicing scientists. Discussions of qualitative interpretations and explanations, for example, hardly ever appear. Likewise, while students can construct misconceptions, they also can construct knowledge that demonstrates clear progress towards scientific understanding. The focus on opposing textbook concepts and student misconceptions — or on opposing textbook equations to students’ knowledge systems — therefore potentially misses much of the developmental action.

We believe, therefore, that future research should not to dismiss computer simulations as learning tools, but should change the curriculum to include a broader range of kinds of scientific knowledge. In particular, the curriculum should include comparing motions, envisioning the evolution of processes of motion, and connecting scientific symbols to commonsense experience. Moreover, educators should take advantage of microworlds as an opportunity to engage students in the process of *doing science*, not just solving textbook problems. In particular, science itself is a social constructive process, involving transformed registrations of the world, the development of satisfactory qualitative (and eventually, quantitative) models, and the use of metaphors to generate integrative explanations. Therefore, the use of computer microworlds can provide an opportunity for students to engage in authentic scientific practices of theory construction.

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